Ph 12
(295/1961)

UDC 621.396.96:550.389.2

ACTA POLYTECHNICA SCANDINAVICA

PHYSICS INCLUDING NUCLEONICS SERIES No. 12

MARTTI TIURI

Investigations of radio reflections from satellite-produced ion trails using 100 Mc CW radar

Finnish Contribution No. 21

Also published as PUBLICATION No. 59 OF THE STATE INSTITUTE FOR TECHNICAL RESEARCH, FINLAND.

HELSINKI 1961

ACTA POLYTECHNICA SCANDINAVICA

. . . a Scandinavian contribution to international engineering sciences

Published under the auspices of the Scandinavian Council for Applied Research

in *Denmark* by the Danish Academy of Technical Sciences

in *Finland* by the Finnish Academy of Technical Sciences, the Swedish Academy of Engineering Sciences in Finland, and the State Institute for Technical Research

in *Norway* by the Norwegian Academy of Technical Science and the Royal Norwegian Council for Scientific and Industrial Research

in *Sweden* by the Royal Swedish Academy of Engineering Sciences, the Swedish Natural Science Research Council, and the Swedish Technical Research Council

Acta Polytechnica Scandinavica consists of the following sub-series:

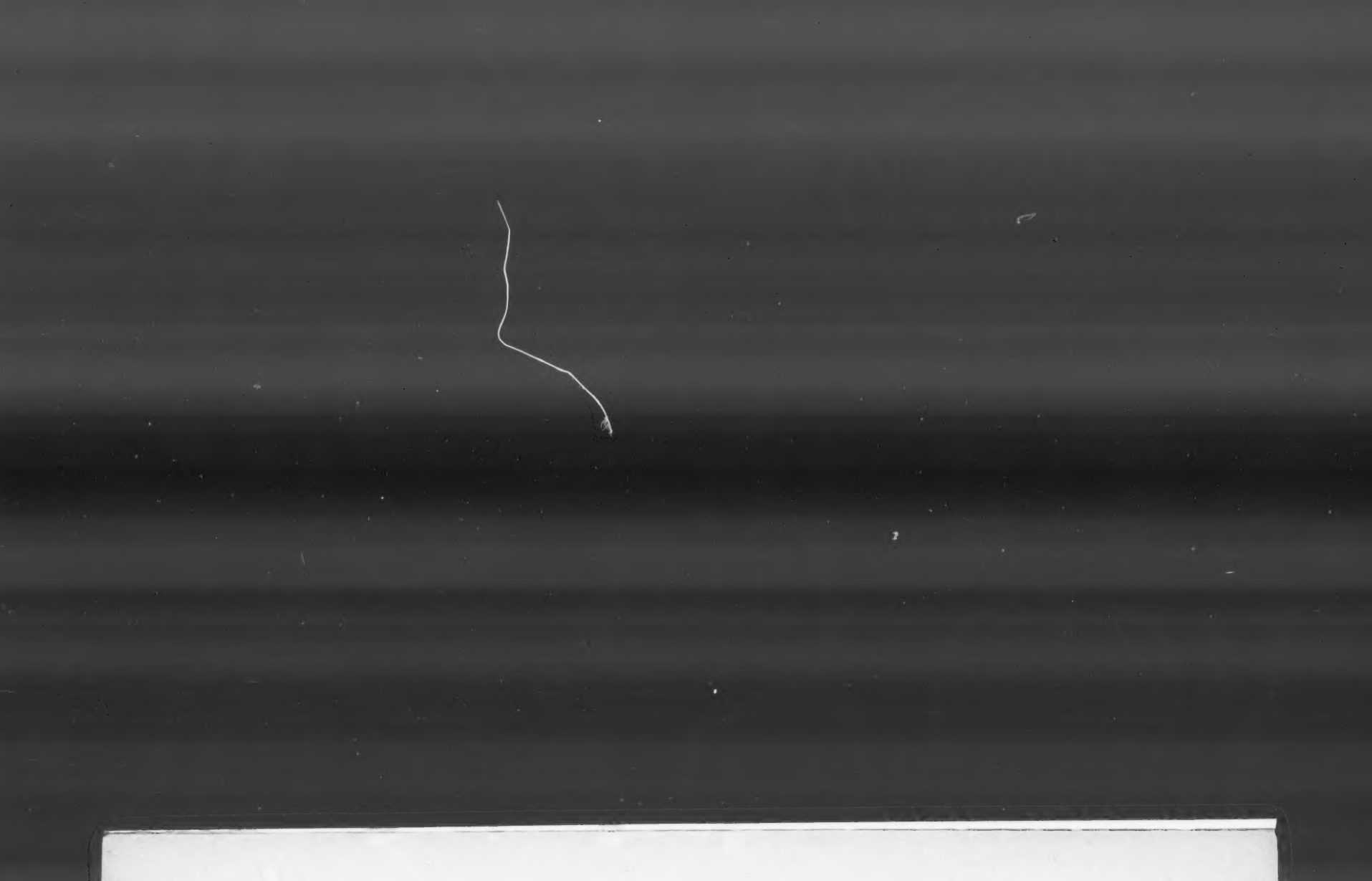
Chemistry including Metallurgy Series, Ch
Civil Engineering and Building Construction Series, Ci
Electrical Engineering Series, El
Mathematics and Computing Machinery Series, Ma
Mechanical Engineering Series, Me
Physics including Nucleonics Series, Ph

For subscription to the complete series or to one or more of the sub-series and for purchase of single copies, please write to

ACTA POLYTECHNICA SCANDINAVICA PUBLISHING OFFICE

Box 5073
Stockholm 5 Phone 67 09 10

This issue is published by
THE STATE INSTITUTE FOR TECHNICAL RESEARCH
Helsinki, Finland



UDC 621.396.9:550.389.2

VALTION TEKNILLINEN TUTKIMUSLAITOS
STATENS TEKNISKA FORSKNINGSANSTALT
THE STATE INSTITUTE FOR TECHNICAL RESEARCH, FINLAND

JULKAISU 59 PUBLICATION

INVESTIGATIONS OF RADIO REFLECTIONS FROM SATELLITE-PRODUCED ION TRAILS USING 100 MC CW RADAR

by

MARTTI TIURI

Thesis for the degree of Doctor of Technology accepted by the Finland Institute of Technology

HELSINKI 1960

VTT Rotaprintpaino 1980

122/7

CONTENTS

	Page
PREFACE	5
INTRODUCTION	7
I. PREVIOUS OBSERVATIONS OF SATELLITE IONIZATION	9
II. OWN INVESTIGATIONS	12
1. CHOICE OF MEASURING SYSTEM	12
1.1 Measuring frequency	12
1.2 Measuring method	13
1.3 Measuring object	14
1.4 Measuring sites	14
1.5 Frequency sweep range and bandwidth of the receiver	15
1.6 Antenna gain	16
2. MEASURING EQUIPMENT	17
2.1 Transmitter	17
2.2 Receiver	19
2.3 Detection range of the equipment	24
3. OBSERVATIONS	24
3.1 Transits of Sputnik III traced	24

3.2 Procedure of the observation 25
3.3 Signals interfering with the observations 26
3.4 Treatment of the material obtained 29
3.5 Satellite echoes 30
3.6 Range measurements 34
4. DISCUSSION OF THE RESULTS 34
4.1 Time of occurrence of the satellite echoes ... 34
4.2 The radar cross section of the ion trail 36
4.3 Conditions for the occurrence of the ion trail 38
4.4 Estimates on the shape and ion density of the 41
ion trail 41
III. SUMMARY 45
REFERENCES 46

PREFACE

The present investigation has been carried out in the years 1959 and 1960 by means of the equipment placed at the author's disposal by the Laboratory of Radio Engineering of the State Institute for Technical Research. I am particularly obliged to the Director of the laboratory, Prof. J. Pohjanpalo, for numerous discussions, which have been greatly beneficial to the progress of this work.

I am also indebted to Mr. B. Kempe, who designed the transmitting antenna used and who worked out the predictions for Sputnik III, and to Mr. Palkee, Mr. Kolari and Mr. S. Seljänperä, who participated in the observations at the receiving station.

I also wish to express my gratitude to the Director of the British Radio Research Station, Mr. R. L. Smith-Rose, who made available to me the observations of Sputnik III's orbit compiled by the said station.

The Finnish Broadcasting Company, Oy Yleisradio, is deserved of my sincere thanks for placing an FM transmitter and the receiving antenna at my disposal.

Finally, I wish to thank Mr. Uljas Attila for help in translating this work.

Helsinki, September 9, 1960

Martti Tiuri

INTRODUCTION

Certain observations which have been made during the last three years indicate that artificial satellites traversing the Earth's atmosphere at an altitude of 100 to 1500 km produce an ionized trail capable of reflecting short radio waves. Krauss (1958), Krauss, Higgy and Albus (1958), Krauss and Dreese (1958), Roberts, Kirchner and Bray (1959), and Krauss, Higgy and Crone (1960), observing the field strength of 5 to 25 Mc radio transmitters at night and far from the transmitter site, noted occasions of momentary increase in the field strength. They attributed this to ionization caused by a satellite passing the point of observation. In France [Flambard, Reyssat; 1958] and in Germany [Dieminger; 1958] signals probably due to ionization by an artificial satellite have been obtained in ionospheric soundings. A negative result concerning the ionization produced by an artificial satellite has been reported by Hendricks, Swenson and Schorn (1958).

The possibly existing ion trail left by an artificial satellite is important for the tracing of the satellite by radar and also when the satellite is used as a passive reflector in long-distance radio communication. In the present investigation the occurrence of ionization has been studied on 100 Mc, with CW and pulse radar, observing the transits of Sputnik III (1958 Delta 2) between August 1959 and April 1960. Contrary to earlier observations, strongly directional transmitting and receiving antennas have been used enabling to achieve higher accuracy in the location of the reflection points of the received signals. The higher measuring frequency has made observations possible also in the daytime.

I PREVIOUS OBSERVATIONS OF SATELLITE IONIZATION

A brief review of earlier results on the subject will clarify the basis of the present work.

Satellite ionization was first studied by Krauss [Krauss; 1958], [Krauss, Higgy, Albus; 1958], [Krauss, Dreese; 1958]. He employed the following method: The field strength of the 20 Mc standard frequency station WWV was measured at nighttime at a distance of 530 km from the transmitter. The electron density in the ionosphere was normally so weak that no signal could be observed. However, temporary local increases in ion density produced observable signals. In most cases these signals were short and could be attributed to meteors, but there were also fairly strong signals lasting from ten seconds to several minutes. Some of these long signals, too, were caused by meteors, but many of them occurred close (within about two minutes) to the time of predicted nearest approach of Sputnik I or II. Also Sputnik III and Explorer I and III were observed in this manner. The altitudes of the artificial satellites varied from 250 to 1500 km. At the time of the last days of Sputnik I there were particularly many long signals. Krauss suggests that they were due to disintegration of the satellite into several pieces. Krauss concludes that an artificial satellite is considerably superior in efficiency to meteors in establishing long-distance radio connections on 20 Mc in the nighttime.

Hendricks, Swenson and Schorn (1958) applied the same principle as Krauss. The receiving antenna was a simple dipole, which enabled at least three consecutive passes of the satellite to be observed. The authors reasoned that if the long signals were caused by satellite-produced ionization, then such signals should occur periodically with a period equalling that of the satellite (about 90 to 100 minutes). The latter changes very little from one pass to the next and, for this reason, the interval between long signals, too, should not vary more than one to two minutes. However, the authors did not find such signals. They concluded that

satellites do not produce ionization, at least when they are travelling extremely high in the ionosphere.

Roberts, Kirchner and Bray (1959) also used the principle of Krauss, listening on the 5, 10, 15 and 20 Mc transmissions of WWV. They report having observed several types of signals positively connected with satellite passes. In addition to the long signals reported by Krauss, a Doppler-shifted signal was observed, which produced audible interference with the direct signal from WWV. On 5, 10 and 15 Mc, signals were received, arriving 8 to 10 minutes after the predicted nearest approach of the satellite. They had durations from a few seconds to nearly one minute. The strongest of these delayed signals came on the lower frequencies.

In addition to the long WWV signals connected with the passes of satellites, Krauss, Higgy and Crone (1960) observed satellite-related signal burst groups in which the centermost burst was the strongest. This took place, for instance, on the 8th of August, 1958, when the rocket of Sputnik III was in the beam of the receiver at an altitude of 800 km and a distance of 2800 km in the northern auroral zone. Bursts had a duration of about one minute and their amplitude increased at first and then decreased. The signal had the character of noise, and the authors think that it was caused by the transit of the satellite through ion clouds of varying density. In their opinion the symmetry of the signal burst group indicates that the reflection from the ion trail of a satellite is specular. The radar cross section corresponding to the strongest burst was several square kilometers. The ionization induced by the satellite must therefore have been very intense. The investigations revealed further that Doppler shifts of the WWV signals occurred in connection with the satellite passes. These Doppler-shifted signals had also the character of noise. The frequency-shifts were, in the 15 Mc range, typically of the order of 5 kc, which is equivalent to a velocity of 40 km/sec. The velocity of the satellite was about 7 km/sec. Hence, according to Krauss, Higgy and Crone, particles initially at rest can be driven ahead of the satellite by an elastic collision at twice this velocity, or about 14 km/sec. This is only a fraction of the observed value 40 km/sec., and some other process of accerelation must be involved in addition. The phenomenon could be due to an encounter of the satellite with fast corpuscular streams. The electric charge of the satellite may increase the collision cross section. If the satellite acquires a negative potential, it will sweep electrons ahead. This produces an accumulation of electrons in front of the satellite and a deficiency behind it. The latter also reflects radio waves. Krauss, Higgy and Crone observed several of the best coincidences between WWV bursts and satellite passes about 24 hours after large solar flares.

Flambard and Reyssat (1958) studied the observation of satellite-produced ion trails with an ionosphere sounder on 25 Mc. According to their estimate, a satellite having 10^6 times the weight of a one-milligram meteor should cause at an altitude of 200 km an electron density one hundred times that produced by the meteor at 100 km. Their calculations included the fact that the air density at an altitude of 100 km is 10^4 times that at 200 km. Ionization of such a mag-

nitude should make ionized trails perpendicular to the antenna beam readily observable with normal ionospheric sounding equipment. Authors assumed that echoes obtained in their measurements originated from satellites if the following conditions were satisfied:

1) The echoes arrived within five minutes, referring to the time of transit through the center of the antenna beam, and from a distance equal to that of the nearest point on orbit.
2) The received echo had a longer duration than the echoes produced by meteors.
3) No other long signals were received within 30 minutes.

There were four signals satisfying these conditions. They lasted about 30 seconds when the satellite passed at 500 km altitude, and 100 to 300 seconds at 250 km. The radar cross sections were several thousand square meters. Only a few of the reflections arrived from trails perpendicular to the antenna beam. The authors consider this as an indication that the structure of the ion trail and the mechanisms of reflection are more complicated than they had assumed. It should be noticed in this connection that Flambard and Reyssat's comparison on the ionizing properties of a satellite and a meteor is misleading. Manning and Eshleman (1959) have shown that an overwhelming part of the meteoric ionization originates from the meteoric substance, and not from the air.

Oblique ionospheric soundings at Lindau, Germany, on 26 Mc, revealed two signals which were considered to be due to satellite ionization [Dieminger; 1958]. One of them seems to indicate that perpendicularity condition is not necessary for the reflection from the ion trail.

As a summary, it can be said that satellite ionization has so far been investigated using frequencies between 5 and 26 Mc. This has been done mainly by observing at nighttime the field strength of standard frequency stations in the long-distance reception area. Many of the particularly long signals are, with high degree of probability, connected with satellite-produced ionization. However, it seems that no statistics on the commonness of the satellite echoes has been made. Further, there are many different ideas on the ionization mechanisms of a satellite-produced ion trail. It is not known wether the reflection is specular or not. The ion density and its distribution are also unknown. Only a few estimates have been published regarding the radar cross section of the ionized trails.

The purpose of the present work is to throw some additional light on these questions.

II OWN INVESTIGATIONS

1. CHOICE OF MEASURING SYSTEM

1.1. Measuring frequency

The investigation of the ionized trails of satellites by means of short waves (10 to 100 meters) is disturbed by interference from long signals caused by meteors, local increases of ion density occurring in the ionosphere, etc. Furthermore, a great number of transmitting stations operate with very small frequency intervals in the short wave range and distant radio stations may therefore produce interfering signals especially in the case of Doppler shift measurements. Daytime observations on short waves are entirely impossible, on account of the high electron density in the ionosphere.

The number of interfering signals might be reduced, and the point of reflection might be determined more precisely, by using strongly directional antennas. This is, however, impractical on short waves because of the large size of such antennas. For this reason it is advantageous to choose a frequency as high as possible. However, the radar cross section of the ion trail as well as the duration of the reflected signal decrease rapidly with increasing frequency. In the case of ion trails produced by meteors, the radar cross section is inversely proportional to the frequency and the duration of the echo proportional to the square of the frequency. This holds up to about 100 Mc [Eshleman; 1955], [Manning, Eshleman; 1959]. Ion trails of artificial satellites have been found to posses on 20 Mc a radar cross section of the order of several square kilometers and the durations of signals reflected from them have been several minutes [Krauss, Dreese; 1958], [Krauss, Higgy, Crone; 1960]. It is likely, therefore, that satellite ionization still can be observed on frequencies up to 100 Mc, and that the reflected signal will have a duration in excess of one second.

Considering the reasons just stated, and the frequency range of FM transmitters available, the frequency 98.82 Mc was chosen for the present work.

1.2. Measuring method

In investigations carried out on 20 Mc, satellite ion trails have been observed as high up as 1500 km [Krauss, Albus, Higgy; 1958]. On 100 Mc the radar cross section of the ion trail is considerably less than on 20 Mc and the measuring system must be highly sensitive in order to enable observations to be made of trails at 1000 to 1500 km. From this point of view a CW radar is advantageous for the reason that the bandwidth of the receiver may be narrow, provided that the Doppler shift of the echo is known. The method requires the use of separate transmitting and receiving antennas. They must be sufficiently spaced to prevent interference by leakage signal reaching the receiver directly from the transmitter. On the other hand, when strongly directional antennas are used the spacing between the transmitter and the receiver should be small. Otherwise the satellite will rarely cross the beams of both antennas simultaneously.

Pulse radar cannot detect as small radar cross sections as CW radar (assuming equal maximum transmitting power). However, the distance information can be used to distinguish between satellite echoes and other similar signals.

Careful consideration of the advantages and drawbacks of different methods of observation resulted in the choice of a CW radar with a transmitter and receiver having fixed directional antennas, and placed as close to each other as possible. A frequency-swept receiver enabling the power spectrum of the reflected signal to be observed was chosen for the reception. As sweep frequency 2 cps was used. Among others, this method has the following advantages:

1) When the frequency sweep range of the receiver is wide enough, the reflected signal will be observed even when its Doppler shift exceeds the bandwidth of the receiver. The receiver may therefore have a narrow bandwidth.
2) The Doppler shift of the reflected signal can be measured and from this information the motion of the ion trail determined.
3) With a sweep frequency of the receiver $\lesssim 2$ cps, most of the meteor signals will be eliminated. This follows from the fact that their duration is less than 0.5 sec. [Manning, Eshleman; 1959]. However, all signals lasting one second or longer will be recorded.
4) As a consequence of the fact that the transmitting and receiving antennas are close to each other, signals from meteors will be as short as possible [Manning, Eshleman; 1959].

In the case that the radar cross section of the satellite ion trail should be found to be sufficiently large, the use of pulse radar measurements was planned in addition to the CW radar measurements.

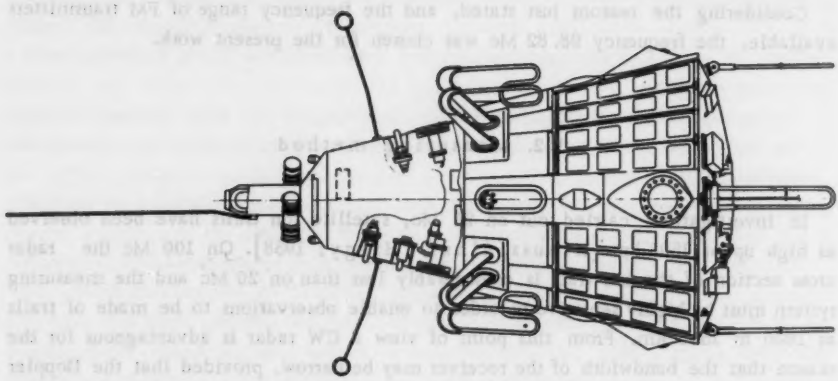


Fig. 1. Sputnik III.

1.3. Measuring object

As measuring objects, Sputnik III (1958 Delta 2) and the Discoverer satellites could be considered. The orbit of Sputnik III was tangent to the latitude circle 65 °N, and the satellite passed over Finland from west to east several times every day. In Southern Finland, using fixed directional antennas pointing to the north, it was therefore possible to observe one to three passes of Sputnik III every day.

The orbits of the Discoverer satellites passed over the north and south poles. Their paths would therefore have crossed fixed antenna beams only a few times every week. Another drawback was the fact that neither as accurate predictions, nor as many optical observations of these satellites, were available as for Sputnik III. The latter was accordingly chosen as the object of measurement.

As is known, Sputnik III had the shape of a cone (Fig. 1). Its length was 357 cm and the diameter of its base 171 cm. On 100 Mc a body of this size has a radar cross section approximately equal to its geometric cross section, in this case accordingly three to four square meters. In some directions the radar cross section may have been doubled by the satellite antennas, but it was probably no more than 10 square meters in any direction.

1.4. Measuring sites

The transmitter was located in Helsinki (60 ° 10' N; 24 ° 50' E) and the receiver at Parola (61 °N; 24 ° 20' E), 95 kilometers NNW of Helsinki. Close to the receiving station at Parola there was a hill, steeply rising 45 meters, which prevented the direct field of the transmitter from reaching the receiver. On account of the location

of the receiving station, the azimuthal orientation 347° (clockwise from the north) was chosen for the transmitting and receiving antennas.

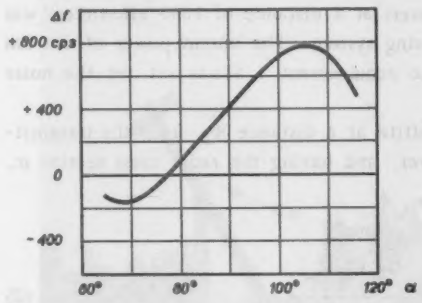


Fig. 2. The Doppler shift Δf of a signal reflected by Sputnik III as a function of the directional angle α of its orbit.

1.5. Frequency sweep range and bandwidth of the receiver

If the ion trail of an artificial satellite is formed partially in front of the satellite, as has been suggested by Krauss et. al., [Krauss, Higgy, Crone; 1960], it can be expected that the point of reflection moves with the satellite. The signal reflected to the receiver may then experience a Doppler shift corresponding to this motion, and this will determine the required frequency sweep range of the receiver.

On 100 Mc the influence of the ionosphere on the Doppler shift is negligible, and the Doppler shift Δf of the signal reflected from the satellite is obtained from the equation

$$\Delta f = \frac{2v}{c} f_o \qquad (1)$$

where v is the radial velocity of the satellite, f_o is the transmission frequency and c the velocity of light. In this equation the transmitter and the receiver have been assumed to be in the same place.

Fig. 2 shows the Doppler shift of a signal reflected by Sputnik III in August 1959, calculated by equation (1) as a function of the directional angle α of its trajectory. The latter is the angle between the meridian and the projection of the trajectory on the earth's surface. It is measured at the point, where the projection intersects a vertical plane having the azimuthal orientation 347° (the azimuth of the main antenna beam). In order to cover possible changes in the orbit, the receiving frequency was chosen to sweep from -500 to +1000 cps on both sides of the transmission frequency. Then with a sweep frequency of 2 cps, the suitable bandwidth for the receiver will be 75 cps, which affords sufficient time for the receiver signal to reach its full value.

1.6. Antenna gain

Considering the altitude of Sputnik III and its radar cross section, the possibility to detect a cross section of 10 square meters at a distance of 1000 kilometers was set as a goal in the design of the measuring system. The output power of the FM transmitter available was 8 kW, and the requirement 1.5 was set for the noise figure of the receiver.

According to the radar equation, a satellite at a distance R_T from the transmitter and at a distance R_R from the receiver, and having the radar cross section σ, will reflect into the receiver the power

$$P_R = \frac{\lambda^2}{64\pi^3} \frac{G_T G_R P_T}{R_T^2 R_R^2} \sigma \qquad (2)$$

λ is the wavelength of the transmitter, G_T the gain of the transmitting antenna in the direction of the satellite, G_R the gain of the receiving antenna, and P_T the transmitted power.

Cosmic noise must also be taken into account in determining the lowest detectable signal level. The noise power P_N referred to the input of the receiver is

$$P_N = \left[(F - 1)\, T_o + T_A\right] \cdot kB \qquad (3)$$

where F is the noise figure of the receiver, T_o = 290 degrees Kelvin, T_A the effective noise temperature of the antenna, $k = 1.38 \cdot 10^{-23}$ joule/degrees Kelvin, and B the bandwidth of the receiver. On 100 Mc the effective noise temperature of the antenna varies between 700 and 7000 degrees Kelvin depending on the orientation of the antenna relative to the Milky Way [Krauss, Ko; 1957].

Assuming a radar cross section of 10 square meters, a distance of 1000 kilometers from the transmitter and from the receiver, 1000 degrees Kelvin average noise temperature of the antenna, 75 cps receiver bandwidth, and a signal-to-noise ratio 10 dB, equations (2) and (3) give: $G_T G_R = 35000$. Provided that identical antennas are used, both must have a gain of nearly 23 dB. This gain is achieved by means of a paraboloid reflector antenna of 230 square meters reflector surface, assuming that the effective area of the antenna is 60 per cent of its geometrical area. There were no facilities for the construction of two antennas of this size. Therefore it was decided that only the transmitting antenna should have a gain of 23 dB. For the receiving antenna, a Yagi array having 15 dB gain was chosen.

The detection range of the final measuring apparatus will be discussed in section 2.3.

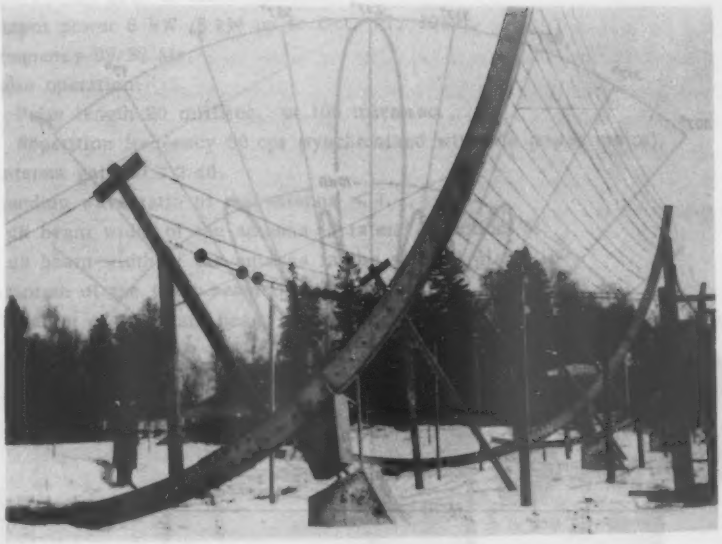


Fig. 3. The radar transmitting antenna.

2. MEASURING EQUIPMENT

2.1. Transmitter

A conventional VHF transmitter (Philips SOZ 337/02) was used. To improve the frequency stability it was provided with a crystal oscillator control (frequency stability $3 \cdot 10^{-8}$) and with the necessary modulator stage for pulse operation.

The transmitting antenna was a fixed paraboloid reflector antenna, constructed for this particular purpose (Fig. 3). The length of the reflector was 31 meters and its width 10 meters. The feeder consisted of a row of dipoles with reflector rods, producing uniform illumination in the longitudinal (horizontal) direction and an illumination diminishing by 6 dB towards the edges in the vertical section of the reflector. The radiation patterns of the antenna in its principal direction and its gain were determined by means of airborne observations. The radiation patterns found are shown in Fig. 4. The accuracy of the measurement of the azimuthal angles was $\pm 2^{o}$.

The measured gain of the antenna was 21 ± 2 dB, which is 3 dB less than the calculated one (for the effective area 0.6 times 310 square meters). The difference is thought to be due to the location of the feeding elements and to an unequal distribution of power in the longitudinal direction of the reflector.

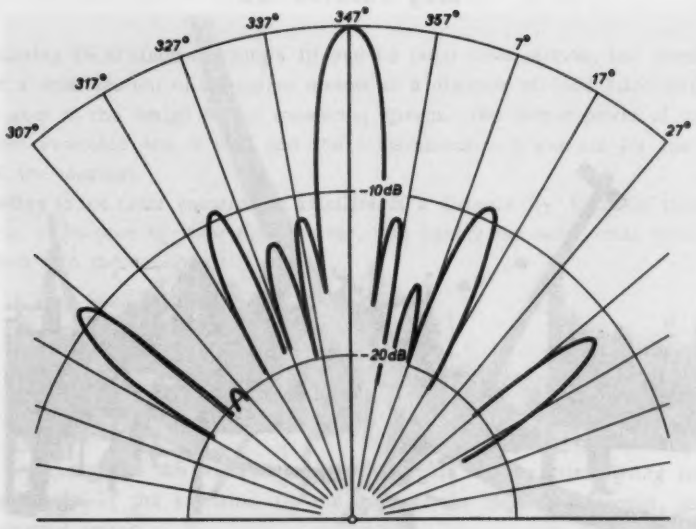


Fig. 4a. Lateral radiation pattern of the transmitting antenna in the plane through the main beam.

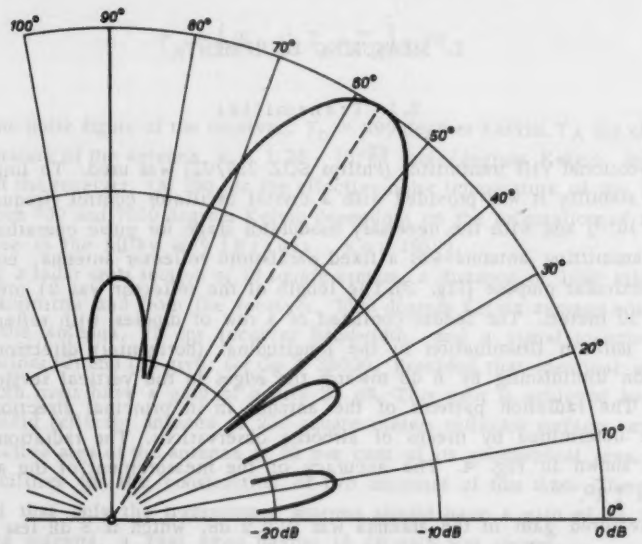


Fig. 4b. Radiation pattern of the transmitting antenna in the vertical plane.

Operational data of the transmitter:
Output power 6 kW (8 kW up to Oct. 27, 1959),
Frequency 98.82 Mc,
Pulse operation:
Pulse length 20 millisec. or 100 microsec.,
Repetition frequency 50 cps (synchronized with the power mains),
Antenna gain 21 ± 2 dB,
Standing wave ratio of the antenna < 1.1,
3 dB beam width of the antenna in lateral direction 7°,
3 dB beam width of the antenna in the vertical plane 16°,
Azimuth of the main beam of the antenna 347°,
Elevation of the main beam of the antenna 57° (65° up to Oct. 27, 1959).

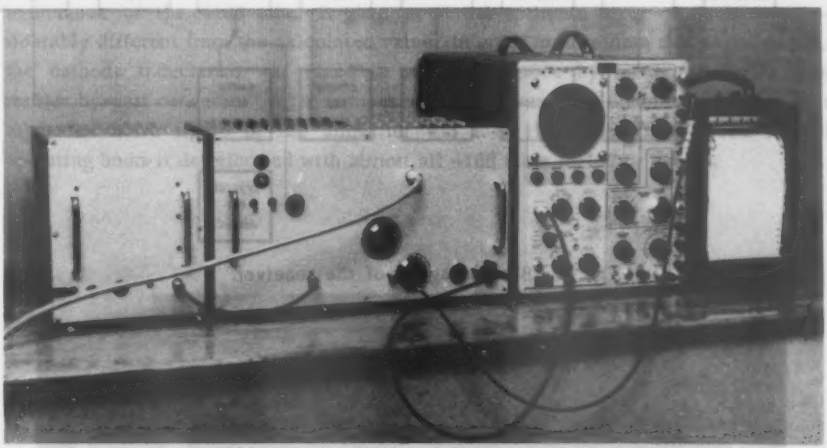


Fig. 5. The radar receiver.

2.2. Receiver

2.2.1. Block diagram

A spectrum analyzer-type receiver was designed to be used in this work (Fig. 5). Its block diagram is seen in Fig. 6. The receiver is a triple super with crystal control for its first two local oscillators (frequency stability $3 \cdot 10^{-8}$). The third local oscillator is frequency modulated. The modulation is linear and controlled by the sweep voltage of an oscilloscope (Tektronix, Type 545). The bandwidth 75 cps of the third (10 kc) IF amplifier determines the overall bandwidth of the receiver. The output signal of the receiver is fed into the oscilloscope, which displays the power spectrum of the received signal. For continuous recording there is a pen recorder (Esterline Angus, Model AW 1 mA DC; chart speed one inch per five minutes), which measures the direct current obtained on rectification of the output signal from the third IF amplifier.

In pulse operation, the third local oscillator of the receiver is also crystal controlled. The signal can be fed to the oscilloscope from a point before the narrowband IF amplifier. The oscilloscope is synchronized with the mains, which also provide synchronization for the transmitter. The bandwidth of the second IF amplifier can be selected to have one of the values 0.5, 1.5 or 6 kc.

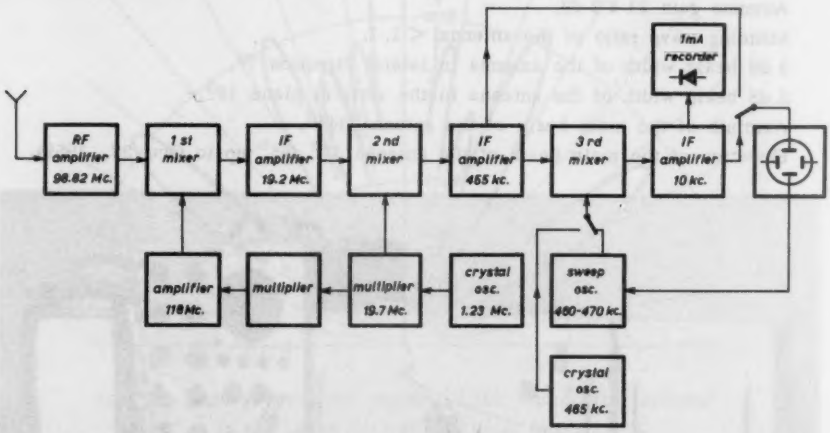


Fig. 6. Block diagram of the receiver.

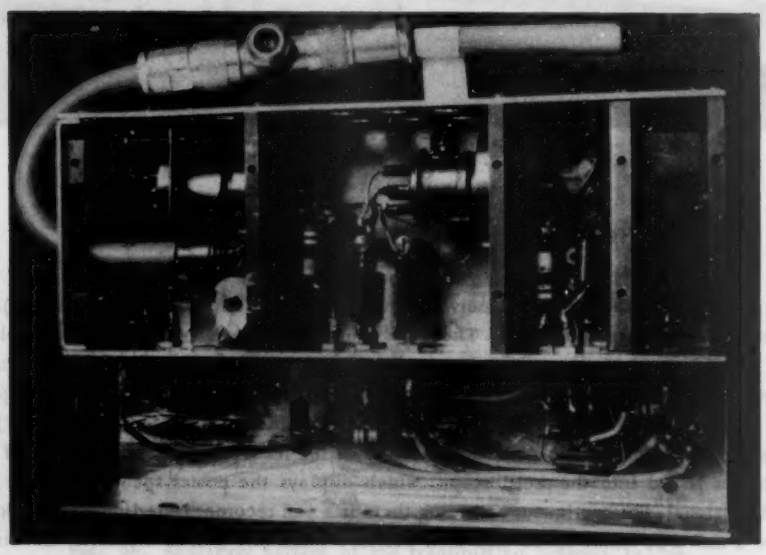


Fig. 7. RF amplifier of the receiver.

2.2.2 Noise figure

Highest possible sensitivity was an essential requirement of the receiver. Because of its low noise figure [Verma; 1958], for the RF pre-amplifier the microwave triode 416B was chosen. It was furthermore decided to employ a cascode input stage and a coaxial resonator made of RG9-U cable for the input circuit (Fig. 7). In comparison with a conventional coil, the latter has the advantage that its impedance transformation ratio can be accurately calculated.

Measurements on the finished RF amplifier revealed that its noise figure was considerably in excess of the calculated optimum value 1.3. The unsatisfactory noise figure was found to be due to the input impedance produced by the cathode inductance of the 416B tube. It gave an actual optimum input conductance considerably different from the calculated value. In order to eliminate this phenomenon, the cathode inductance was tuned to series resonance by means of the cathode resistor by-pass condensor. After compensation of the cathode inductance, with best tubes the noise figure of the amplifier was 1.4. However, within a few tens of operating hours it deteriorated with almost all 416B tubes to 1.7 or even 2.

Fig. 8. The radar receiving antenna.

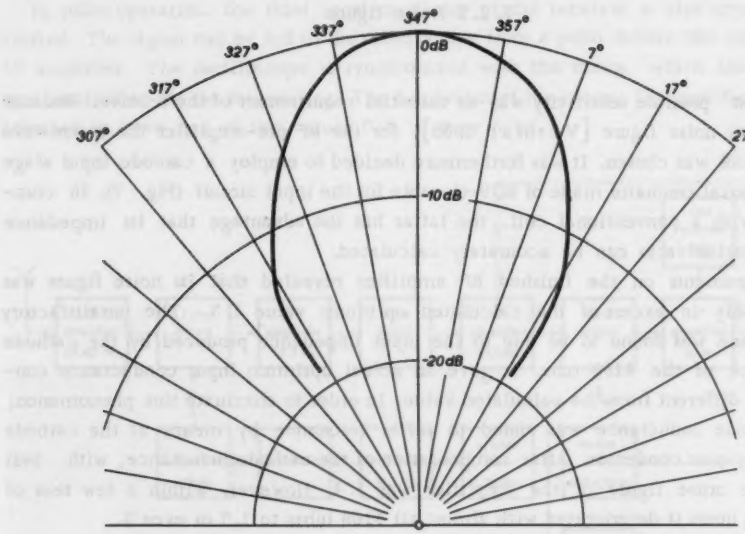


Fig. 9a. Lateral radiation pattern of the receiving antenna in the plane through the main beam.

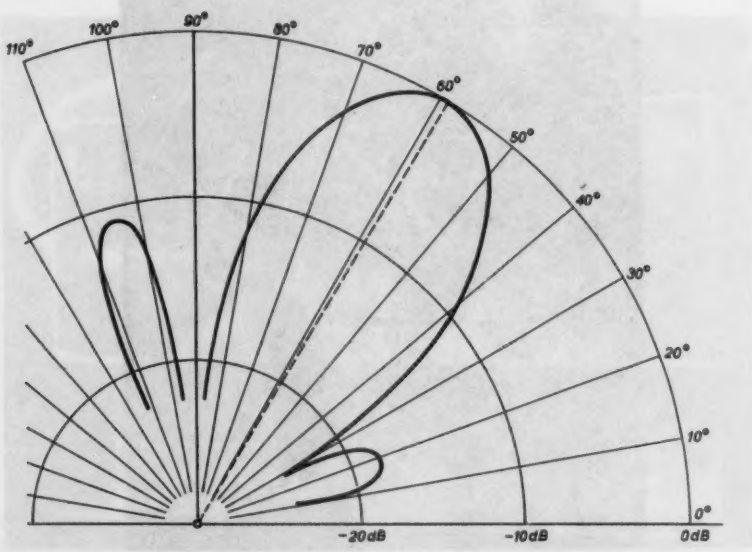


Fig. 9b. Radiation pattern of the receiving antenna in the vertical plane.

2. 2. 3. Operational data of the receiver

Eight three-element parallel-coupled Yagi antennas were used as the receiving antenna (Fig. 8). The radiation patterns of the array in its principal planes, as well as the gain, were determined by airborne observations. Fig. 9 shows the radiation patterns found.

Operational data of the receiver:

Input impedance 50 ohms,
Noise figure 1. 4 to 2. 0,
Bandwidth, in CW operation 75 cps,
in pulse operation 75, 500, 1500 or 6000 cps,
Frequency 98. 82 Mc (tuning range 10 kc),
Sweep frequency 2 cps,
Antenna gain 15 ± 1 dB,
Standing wave ratio of the antenna < 1.3,
3 dB beamwidth of the antenna in lateral direction 27°,
3 dB beamwidth of the antenna in vertical plane 21°,
Azimuth of the main beam of the antenna 347°,
Elevation of the main beam of the antenna 59° (69° up to Oct. 27, 1959).

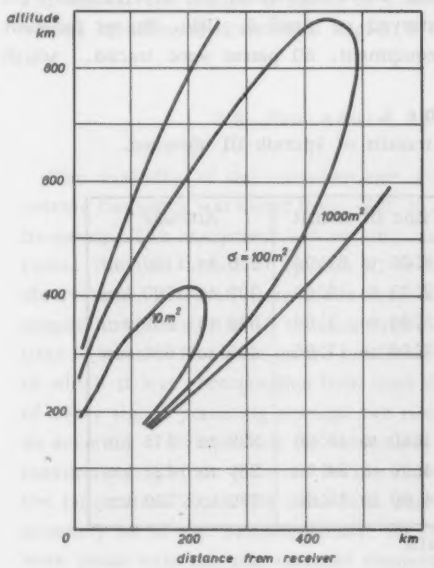


Fig. 10. Minimum detectable radar cross section as a function of the altitude and distance of the target.

2.3. Detection range of the equipment

The maximum detection range of the measuring equipment is determined by the operational data of the transmitter and the receiver, and the minimum detectable signal in the receiver.

In CW measurements, with a 75 cps bandwidth, the noise power of the receiver, referred to its input, is -179 dBW (dB below one watt). This follows from equation (3), when the noise figure of the receiver equals 2 and the effective temperature of the antenna is 1000 degrees Kelvin. According to the measurements made, a signal could be detected with certainty on the oscilloscope screen when it exceeded the noise by 10 dB. The weakest detectable signal was thus -169 dBW, or 25 nanovolts at the receiver input.

Fig. 10 shows the distances at which targets with radar cross sections of 1000, 100 and 10 square meters, respectively, can be detected in the main beams of the antennas (after Oct. 27, 1959), as calculated from equation (2).

3. OBSERVATIONS

3.1. Transits of Sputnik III traced

Observations of the transits of Sputnik III were started in August 1959 after that the measuring equipment had been finished. Since September 24, observations were made daily until the satellite was destroyed on April 6, 1960. Except for short interruptions caused by failures in the equipment, all passes were traced, which

Table 1.
Monthly distribution of the transits of Sputnik III observed.

1959	Number	Time of transit	Altitude
August-September	24	8:00 to 21:00	850 to 1100 km
October	38	2:00 to 9:00	700 to 1000 km
November	47	15:00 to 1:00	525 to 850 km
December	50	7:00 to 17:00	425 to 650 km
1960			
January	43	21:00 to 10:00	320 to 575 km
February	37	14:00 to 24:00	260 to 420 km
March-April	43	4:00 to 17:00	190 to 330 km

Altogether 282 transits

Table 2.

Diurnal distribution of the transits of Sputnik III observed.

Time of transit	Number
0: 00 to 4: 00	23
4: 00 to 8: 00	57
8: 00 to 12: 00	59
12: 00 to 16: 00	52
16: 00 to 20: 00	50
20: 00 to 24: 00	41

Table 3.

Directional angles of the transits of Sputnik III observed

α	Number
60° to 70°	44
70° to 80°	56
80° to 90°	40
90° to 100°	47
100° to 110°	50
110° to 120°	45

fell into the main beams. Their number was on the average two per day. Observations were made during about 170 days.

The directional angle α (cf. 1.5) and the altitude, as well as the time of transit through the antenna main beam, were calculated on the basis of predictions obtained from U.S.A. (National Aeronautics and Space Administration) and England (Radio Research Station).

The distribution of the transits traced in the different months is shown in Table 1. The diurnal distribution is shown in Table 2. Table 3 shows the distribution of the transits to different directional angles α of the trajectory.

3.2. Procedure of the observation

The majority of the measurements were carried out in CW operation. The receiving frequency was swept from -500 to +1000 cps on both sides of the transmission frequency. The equipment was working continuously daily from about one half hour before the first transit of Sputnik III to one half hour after its last transit. Actual observations, however, were made only during the half an hour (in 1959 during 20 minutes), which started 15 minutes before and ended 15 minutes after the predicted time of transit. The trace on the oscilloscope screen was followed visually in addition to which it was photographed from time to time. The following data were recorded of every signal persisting through two sweeps, or longer: time of occurrence within an accuracy of five seconds (in some cases ten seconds), duration (number of sweeps), maximum amplitude (referred to the receiver input) with 25 nanovolts accuracy in the range from 25 to 200 nanovolts, and the mean frequency of the signal with an accuracy of 75 cps. Simultaneously, for later checks of the observations, recordings were made with the pen recorder connected to the receiver.

The transmitting power was checked daily by means of an output meter in the transmitter. The measuring antennas were checked by means of standing wave measurements. The gain of the receiver was calibrated once every week by means of a signal generator (HP 608 C). The tuning of the receiver (i. e., the place of the CW signal on the oscilloscope screen) was checked at the beginning and at the end of each period of observation. This was done by means of the direct signal from the transmitter, received through an auxiliary antenna on the top of the hill at the receiver site. The time (Finnish Standard Time = U. T. + 2^h) was read from a chronometer, which was compared daily with the time signals transmitted by the Finnish Broadcasting Company.

Range measurements were carried out on ten days only. For this, as a rule, a 20 milliseconds pulse length and 500 cps bandwidth were used. The modulator of the transmitter was synchronized with the mains, as was also the range indication oscilloscope. The zero point of the range scale was determined by means of the auxiliary antenna, situated on the top of the hill. The accuracy of the range measurements was about ± 75 kilometers. When a lower accuracy was sufficient, 75 cps bandwidth could be used with a 20 milliseconds pulse length.

3.3. Signals interfering with the observations

Various kinds of signals interfering with the satellite observations could be seen. Most of these signals were caused by meteors and their duration was less than 0.5 seconds. They occurred at an average rate of three or four within ten minutes, being most abundant at about 6 hours and least at about 18 hours, in accordance with the density of occurrence of meteors.

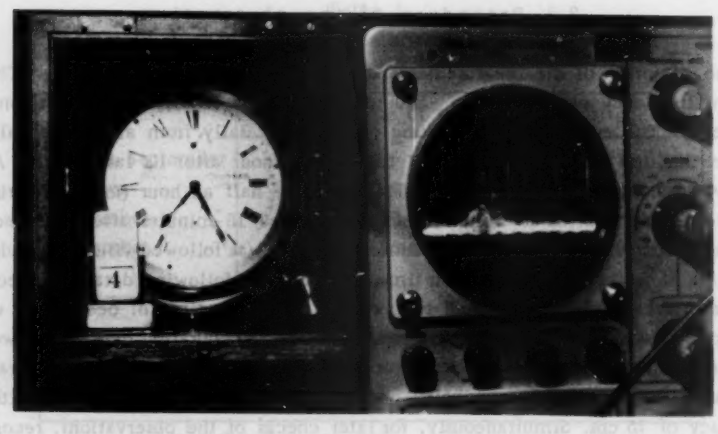


Fig. 11. Typical long meteor echo (at 7:25 hours on Jan. 4, 1960).

There were also meteor signals of two or more sweeps, particularly in the morning, but, as a rule, there was less than one such signal in half an hour. However, long meteor bursts were observed in exceptional numbers on some days, e.g., January 4, 1960 (Quadrantides). Is was confirmed by measurements carried out in August, 1959 that some of the long meteor signals could be associated with meteors that were visible in the sky. Long meteor bursts were characterized by high amplitude, ≥ 200 nanovolts, rapid variation of amplitude and often Doppler shifts greater than 150 cps. In most cases the amplitude was highest at the beginning of the signal. An oscilloscope photograph of a typical, long meteor burst is shown in Fig. 11.

Aeroplanes above the receiving station produced echoes, which generally lasted 10 to 30 seconds. They could be recognized easily because, at the same time, the noise of the aircraft could be heard. Naturally they have not been taken into account as actual signals.

The hill close to the receiving station could not always prevent the direct signal from the transmitter. There were five days on which a continuous signal of 25 to 50 nanovolts amplitude was present in the receiver, obviously as a result of exceptional propagation conditions in the troposphere.

Signals caused by auroral ionization were observed in considerable number, altogether on 24 days. This arose from the fact that, after the change of elevation angle on October 27, 1959, the side lobes of the transmitting and receiving antennas became, at the altitude of 90 to 120 km, perpendicular to the earth's magnetic lines of force. The main part of the auroral ionization takes place at this altitude [Unwin; 1958]. No auroral echoes were observed before the said date. These echoes were of varying duration, from a few minutes to several hours. A typical auroral echo is shown in Fig. 12. The signal has the character of noise and is spread over a frequency range of nearly 1000 cps, about 500 cps on both sides

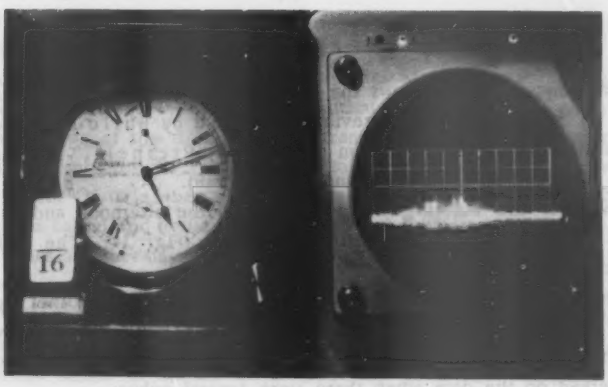


Fig. 12. Typical auroral echo (at 17:12 hours on Feb. 16, 1960).

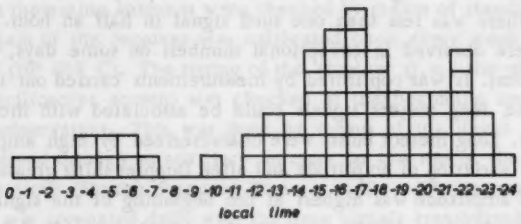


Fig. 13. Diurnal distribution of auroral echoes (each square corresponds to an echo during one hour sampling periods).

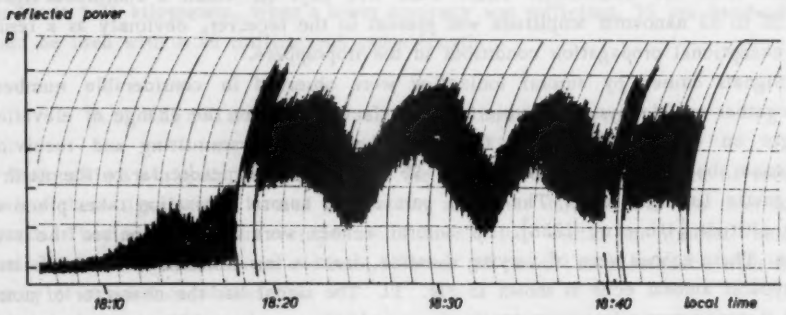


Fig. 14. Recorder chart of periodical auroral reflection on Nov. 23, 1959. The signals at 18:18 and 18:40 hours are due to calibration.

of the CW frequency. Fig. 13 shows the diurnal distribution of the auroral echoes. It is similar in character to that previously observed by Bullough and Kaiser (1955), but differs from the distribution presented by Presnell, Leadabrand, Peterson, Dyce, Schlobohm and Berg (1959).

The intensity of the auroral echoes occuring in the afternoon and early hours of the night was frequently periodically fluctuating (Fig. 14). The period was 7 to 10 minutes [Tiuri; 1960].

The presence of strong auroral echoes made the observation of other signals impossible. For this reason, there were 27 transits of Sputnik III during which the echoes possibly produced by the satellite could not be observed. Only 21 transits could be observed on the days when there were auroral echoes.

3.4. Treatment of the material obtained

In order to distinguish the satellite echoes from other ones, in further treatment only such signals have been considered which were visible on the oscilloscope at the least during two sweeps (cf. 1.1). In the following such signals will be called long signals. Signals visible during one sweep only were not taken into account because they were so numerous that accidental coincidences with the satellite transits were statistically probable.

Long signals occurring during the time interval ± 10 min. from the time of transit were included in the statistics, except auroral echoes lasting at the least one minute. However, if three or more long signals were recorded during this interval, all of them were excluded. This was done because long signals occurred in such an abundance usually on such days only when there was a meteoric shower. For this reason observations during 15 transits were left out altogether.

Each observed long signal was compared with the time of transit of Sputnik III through the antenna main beam. As the predicted times were inaccurate, the actual ones (i.e., the times when Sputnik III crossed the vertical plane with the azimuth 347°) were calculated afterwards. For these calculations, the visual observations made at the meteorological station of Jokioinen and the times when the satellite passed through the northernmost point of the orbit, calculated by the British Radio Research Station (RRS) on the basis of visual and radio observations (Satellite Prediction Service Bulletin No. 5, 1960), were available. The observations made at Jokioinen are accurate within 0.1 sec. in time and 0.1 degrees in direction, while the accuracy of the times from the RRS is given as ± 5 sec. (in some cases ± 10 sec.). According to an estimate of the RRS, their data and the orbital positions given in the predictions give any location of the satellite with a probable error of ± 50 km. Correspondingly, the accuracy of the altitude is ± 20 km.

In determining the times of transit, it was attempted to carry out the calculations with an accuracy of ± 0.1 min. The possibilities of error were reduced by the fact that, even under most unfavourable conditions, the time of transit through the antenna main beam did nor differ more than about three minutes from that through the northernmost point. There are several days when the station at Jokioinen, as well as the RRS, give the data for one revolution of Sputnik III only. In such cases, for the calculation of the times of other transits, the period was assumed to equal that given in the prediction. The error due to this procedure is estimated to be less than ± 0.1 min. On days when no observations of the orbit were available, the times of transit were calculated by interpolation, using the differences between observed and predicted times on other days. There were rarely more than two consecutive days when this was necessary and the resulting error is estimated to be less than ± 0.4 min.

It can be concluded that the maximum error of the time of transit of Sputnik III thus calculated is usually ± 0.4 min., in some cases ± 0.8 min.

The actual times of transit differ from the predicted times by one to three minutes, on the average, the greatest difference being 9 min.

3.5. Satellite echoes

Fig. 15 gives a histogram of the long signals during the different months, referred to the calculated time of transit of Sputnik III, while Fig. 16 represents the sum values of Fig. 15 (97 long signals in all). The histograms show an evident maximum at the time of transit of the satellite. For instance, there are 20 long signals in December, 1959, of which 7 coincide with the time of transit within ± 0.7 min. The probability that 7 signals out of 20 (during 20 minutes) would occur fortuitously in this interval is negligible, in fact less than 0.0005. A considerable part of these signals must, therefore, be echoes produced by the satellite. It will be show later that the radar cross sections corresponding to the echoes always are of the order of several tens, and even several thousands, of square meters, therefore, reflection from the body of the satellite is out of the question. The echoes are thus obviously

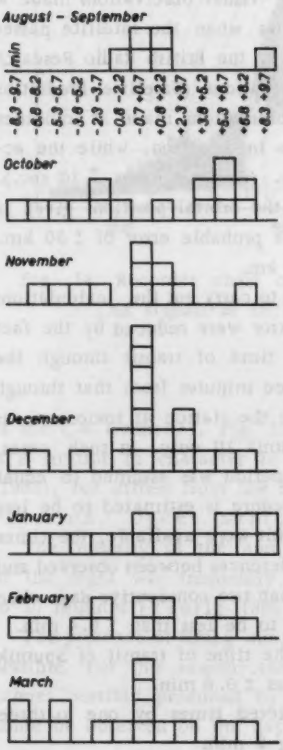


Fig. 15 Monthly histograms of long signals referred to the times of transit of Sputnik III through the antenna main beam. Each square corresponds to one long signal.

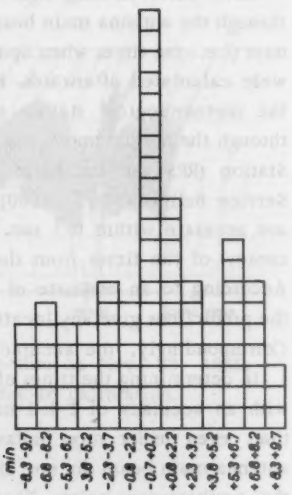


Fig. 16. Histogram of the long signals referred to the times of transit of Sputnik III through the antenna main beam.

Table 4.

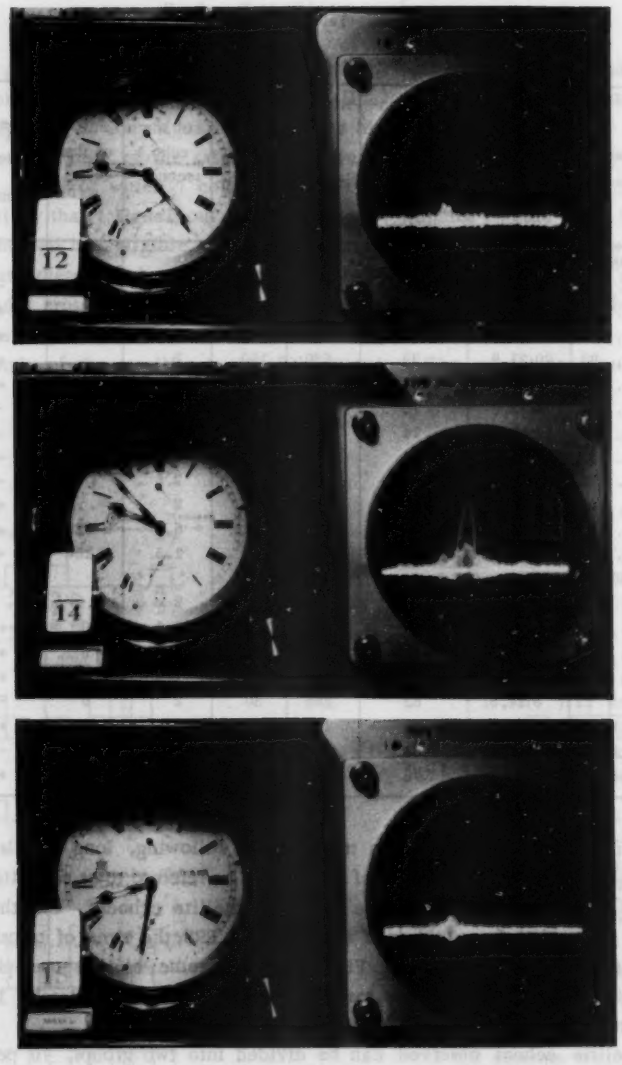
Observed satellite echoes.

Echo No	Date	Calculated transit of Sputnik III, Finnish Standard Time	Directional angle of the trajectory degrees	Altitude of the satellite km	Amplitude of the echo, nanovolts	Duration of the echo, seconds	Doppler shift of the echo, cps	Time difference $T_{echo} - T_{transit}$, minutes
	1959							
1	Aug. 26	(19:50.4)	100	1040	75	2	0	- 0.4 M
2	Sept. 9	(16:38.0)	100	1010	25	5	0	+ 0.5
3	Nov. 17	20:50.8	92	655	75	1	..	+ 0.4 M
4	Nov. 20	20:31.9	99	630	100	2	..	+ 0.7 M
5	Nov. 25	19:49.3	104	600	25	2	0	+ 0.5
6	Dec. 7	14:02.3	74	635	175	1	..	- 0.3
7	Dec. 14	12:00.6	74	640	100	2	0	- 0.2
8	Dec. 15	(11:40.3)	73	590	75	9	0	- 0.5
9	Dec. 21	(9:32.7)	67	605	50	2.5	..	- 0.4
10	Dec. 21	(11:10.3)	87	550	100	2	..	+ 0.4 M
11	Dec. 30	7:22.9	71	540	25	5.5	0-225	+ 0.1
12	Dec. 30	10:38.1	116	420	75	1.5	+ 150	+ 0.5
	1960							
13	Jan. 12	3:46.9	73	530	150	2	..	0.0
14	Jan. 15	3:34.7	80	450	50	1.5	0	+ 0.3
15	Feb. 11	22:04.8	113	315	75	1.5	0	+ 0.4
16	Feb. 15	(18:18.2)	79	360	25	1	0	+ 0.5
17	March 12	(9:24.5)	63	285	50	2	0	- 0.2
18	March 14	9:53.0	78	270	200	2	+ 75	+ 0.7 M
19	March 15	8:32.1	64	280	125	4	- 75	- 0.5
20	March 25	6:28.1	76	240	200	1	..	+ 0.4 M

caused by the satellite-produced ion trail. In the following, long signals received within ± 0.7 minutes from the time of transit will be referred to as satellite echoes.

Table 4 represents a list of all the observed satellite echoes. On those days when there are no data from Jokioinen nor from the RRS, the time of transit through the antenna beam is in brackets. Fig. 17 shows some oscilloscope photographs (exposure time two seconds) of the satellite echoes obtained in March, 1960, and Fig. 18 some typical pen records of the satellite echoes.

The satellite echoes observed can be divided into two groups. 70 per cent of them are characterized by an amplitude changing nearly uniformly, the maximum being at the middle (e.g., the echo of Dec. 14, 1959, Fig. 18 b). The power usually tended to concentrate on frequencies close to the CW frequency, the spread being about 100 to 400 cps, and the maximum power on the CW frequency. A change of the Doppler shift during the echo was observed once only, i.e., at 7:23 hours on Dec. 30, 1959. The echo appeared on the CW frequency but shifted during five seconds to a frequency about 225 cps lower. If the echo observed on



a.

b.

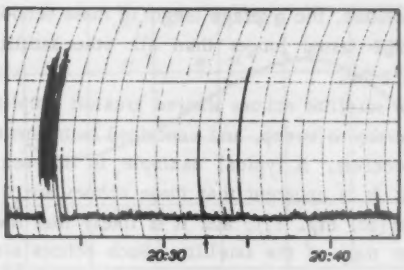
c.

Fig. 17. Typical satellite echo oscillograms.

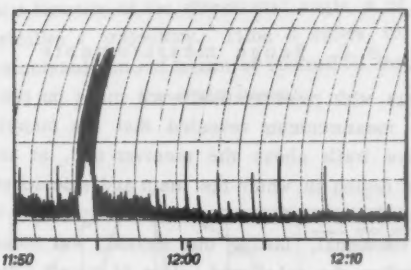
a. Satellite echo No. 17 at 9:24.5 hours on March 12, 1960. (Clock time correction +41 seconds).

b. Satellite echo No. 18 at 9:53.0 hours on March 14, 1960. (Clock time correction -3 seconds).

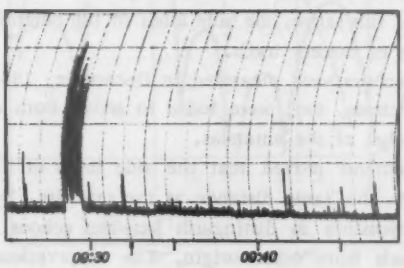
c. Satellite echo No. 19 (the end) at 8:32.1 hours on March 15, 1960. (Clock time correction -1 second).



a.



b.



c.

Fig. 18. Typical records of satellite echoes. Signals of one minute duration are due to receiver calibration.

a. Satellite echo No. 4 on Nov. 20, 1959.

b. Satellite echo No. 7 on Dec. 14, 1959 (auroral reflection at 11:50 to 12:00 hours).

c. Satellite echo No. 9 on Dec. 21, 1959.

Dec. 15, 1959 is excluded, the average length of these echoes is 2.5 seconds. The echo of Dec. 15, 1959 lasted longer than all other satellite echoes and rather resembled an aircraft echo.

30 per cent of the satellite echoes showed greatest amplitude at the beginning, varied rapidly from sweep to sweep, and contained components almost in the entire sweep range of the receiver. A typical example is the echo observed on March 14, 1960 (Fig. 17 b). It is apparent that these echoes are similar in character to the long meteor bursts (cf. Fig. 11), and it is likely that they are due to meteors rather than to the ion trail of the satellite. Such echoes are distinguished by the letter M in Table 4. The average length of these echoes is 1.5 seconds. The average length of the long signals, satellite echoes excluded, is 2.0 seconds.

3. 6. Range measurements

Range measurements with pulse method were made on ten days during a total of eight hours. These measurements revealed that the majority of all the signals were caused by meteor trails above the receiver site, at an average altitude of 100 km. This was the region in which the main and side lobes of the transmitting and receiving antennas intersected.

On Dec. 7, 1959 a signal, lasting one second, was measured at the satellite range, 0.3 minutes before the calculated time of transit (Table 4).

A few times long echoes were observed, arriving from a distance of 500 to 700 km, and not connected to the satellite. It seems probable that the echoes were due to meteors because, at this range, the side lobes of the antennas intersected at the altitudes of occurence of meteor trails.

Ranges of auroral echoes were measured in December, 1959 and in January and April, 1960. These echoes, too, were found to arrive from a distance of 500 to 700 km in the side lobes of the antennas.

The range measurements proved that the side lobes of the antennas gave rise to meteor echoes from the same distance as the satellite. By range measurement it was, therefore, impossible to distinguish between echoes from the ion trail of the satellite and signals from other origin. The observations were, accordingly, mainly carried out by the more sensitive CW method.

4. DISCUSSION OF THE RESULTS

4.1 Time of occurrence of the satellite echoes

It can be seen from Table 4 that a considerable number of the satellite echoes have been received between 0.4 and 0.7 minutes after the calculated transits of Sputnik III. This might indicate that the development of the ion trail takes 0.4

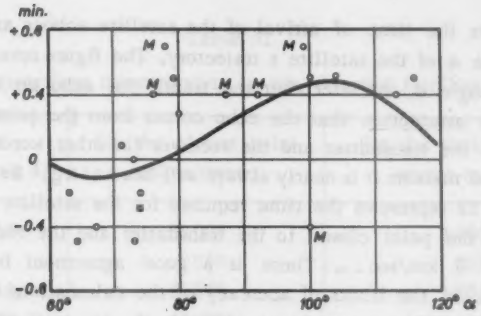


Fig. 19. Time of arrival of the satellite echoes as a function of the directional angle α of the satellite's trajectory. Time 0 refers to the calculated time of transit of Sputnik III through the main beam.

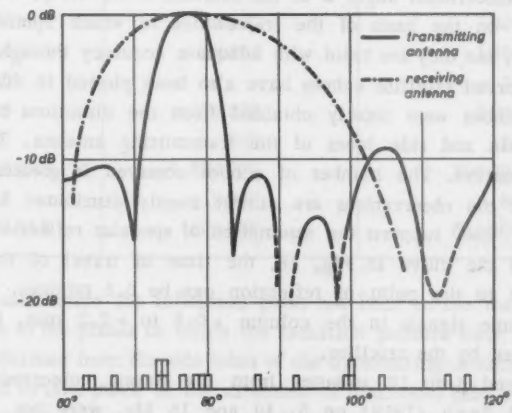


Fig. 20. Relative gains of the transmitting and receiving antennas in the direction of the closest point of the orbit of Sputnik III as a function of the directional angle α of the satellite's trajectory. Gains are shown in the same plane as radiation patterns in Fig. 4a and 9a.

to 0.7 minutes before reflection is possible. Remembering that the echoes last a few seconds only, this is improbable.

Dec. 15, 1959 is excluded, the average length of these echoes is 2.5 seconds. The echo of Dec. 15, 1959 lasted longer than all other satellite echoes and rather resembled an aircraft echo.

30 per cent of the satellite echoes showed greatest amplitude at the beginning, varied rapidly from sweep to sweep, and contained components almost in the entire sweep range of the receiver. A typical example is the echo observed on March 14, 1960 (Fig. 17 b). It is apparent that these echoes are similar in character to the long meteor bursts (cf. Fig. 11), and it is likely that they are due to meteors rather than to the ion trail of the satellite. Such echoes are distinguished by the letter M in Table 4. The average length of these echoes is 1.5 seconds. The average length of the long signals, satellite echoes excluded, is 2.0 seconds.

3. 6. Range measurements

Range measurements with pulse method were made on ten days during a total of eight hours. These measurements revealed that the majority of all the signals were caused by meteor trails above the receiver site, at an average altitude of 100 km. This was the region in which the main and side lobes of the transmitting and receiving antennas intersected.

On Dec. 7, 1959 a signal, lasting one second, was measured at the satellite range, 0.3 minutes before the calculated time of transit (Table 4).

A few times long echoes were observed, arriving from a distance of 500 to 700 km, and not connected to the satellite. It seems probable that the echoes were due to meteors because, at this range, the side lobes of the antennas intersected at the altitudes of occurence of meteor trails.

Ranges of auroral echoes were measured in December, 1959 and in January and April, 1960. These echoes, too, were found to arrive from a distance of 500 to 700 km in the side lobes of the antennas.

The range measurements proved that the side lobes of the antennas gave rise to meteor echoes from the same distance as the satellite. By range measurement it was, therefore, impossible to distinguish between echoes from the ion trail of the satellite and signals from other origin. The observations were, accordingly, mainly carried out by the more sensitive CW method.

4. DISCUSSION OF THE RESULTS

4.1 Time of occurrence of the satellite echoes

It can be seen from Table 4 that a considerable number of the satellite echoes have been received between 0.4 and 0.7 minutes after the calculated transits of Sputnik III. This might indicate that the development of the ion trail takes 0.4

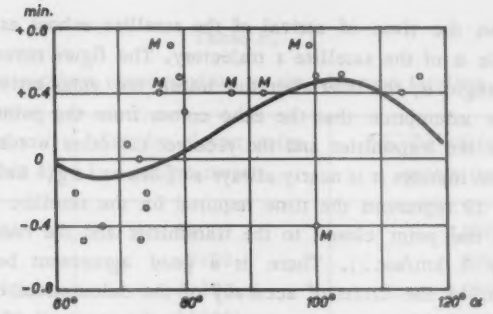


Fig. 19. Time of arrival of the satellite echoes as a function of the directional angle α of the satellite's trajectory. Time 0 refers to the calculated time of transit of Sputnik III through the main beam.

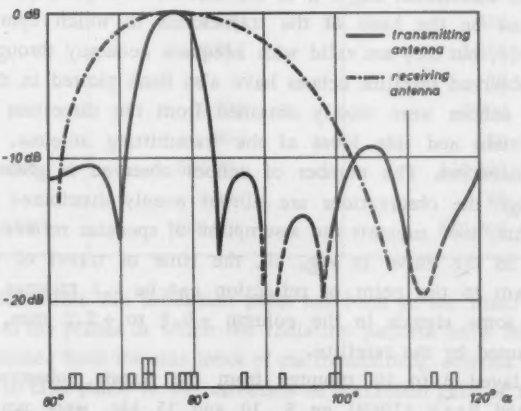


Fig. 20. Relative gains of the transmitting and receiving antennas in the direction of the closest point of the orbit of Sputnik III as a function of the directional angle α of the satellite's trajectory. Gains are shown in the same plane as radiation patterns in Fig. 4a and 9a.

to 0.7 minutes before reflection is possible. Remembering that the echoes last a few seconds only, this is improbable.

Fig. 19 shows the time of arrival of the satellite echoes as a function of the directional angle α of the satellite's trajectory. The figure reveals that, as a rule, the greater the angle α, the later after the transit the echo arrives. An explanation is found in the assumption that the echo comes from the point of the satellite's orbit closest to the transmitter and the receiver (in other words, the reflection is specular). For the meteors it is nearly always so [Manning, Eshleman; 1959]. A curve in Fig. 19 represents the time required for the satellite to travel from the main beam to the point closest to the transmitter and the receiver (assuming an orbital velocity 7 km/sec.). There is a good agreement between the theory and observation. In the limits of accuracy of the calculations of 20 echoes, only four do not agree. This proves that on 100 Mc the ion trail of a satellite can be observed only at right angles to the trajectory (when the distance between the transmitter and the receiver is small in comparison with their distance from the satellite).

The zeros of the main beam of the transmitting antenna were only 12 degrees apart. Therefore, some of the satellite echoes must have come from the side lobes of the antenna. Fig. 20 gives the gains of the transmitting and the receiving antennas in the direction pointing to the closest point of the orbit, as a function of the directional angle α of the satellite's trajectory. These curves have been calculated on the basis of the trajectories in which Sputnik III moved in December, 1959, but they are valid with adequate accuracy throughout the investigation. The observed satellite echoes have also been plotted in this figure. It can be seen that echoes were mostly obtained from the directions of the maximum gain of the main and side lobes of the transmitting antenna. This supports the suggested explanation. The number of echoes observed is greatest for the main beam, although the observations are almost evenly distributed in all directions (Table 3). This, too, supports the assumption of specular reflection.

According to the curve in Fig. 19, the time of travel of the satellite from the main beam to the point of reflection can be 0.5 minutes. Therefore, it is possible that some signals in the column +0.8 to +2.2 min. in Fig. 16 may have been caused by the satellite.

Echoes delayed 8 to 10 minutes from the transit, observed by Roberts, Kirchner and Bray (1959) on 5, 10 and 15 Mc, were not observed in the present investigation.

4.2. The radar cross section of the ion trail

The radar cross sections corresponding to the observed satellite echoes can be calculated by means of equation (2). It has already been demonstrated that the reflection from the ion trail obviously takes place at the closest point of the trajectory. Consequently, the antenna gains and the distances in this particular direction have to be inserted in equation (2). Table 5 gives the radar cross sections thus

Table 5.

Radar cross sections corresponding to the observed satellite echoes.

Echo No. (Table 4)	For the closest point, square meters	For the main beam, square meters
1 (M)	62 000	1 000
2	6 000	200
3 (M)	45 000	1 600
4 (M)	61 000	2 500
5	4 800	45
6	1 900	1 500
7	600	500
8	400	200
9		350
10 (M)	70 000	9 500
11	200	25
12		300
13	1 500	800
14	2 700	1 300
15		70
16	2 200	2 000
17	900	20
18 (M)	500 000	500 000
19	2 300	80
20 (M)	600 000	600 000

calculated in cases where the reflection point has been in the main beams of the antennas or close to the planes in which the radiation patterns have been measured. For the echoes obtained from the side lobes of the transmitting antenna the reflection has been assumed to take place in the direction of maximum gain of the lobe. The azimuths of the side lobes and the antenna gain are not known sufficiently accurately to justify a more detailed analysis. Further, the effect of the standing wave ratio of the receiving antenna should be taken into account. Hence, the figures in Table 5 can be considered as approximate only.

The radar cross sections can be divided into two groups. Most of them are less than 6 000 square meters, while the rest exceed 40 000 square meters. Among others, signals denoted with M in Table 4 have large radar cross sections. As pointed out before, these signals are probably caused by meteors. Accordingly, such radar cross sections are not true radar cross sections. It follows that, on 100 Mc, the radar cross section of a satellite-produced ion trail does not exceed 6 000 square meters.

Among the values of the radar cross sections in Table 5, those are the most accurate which refer to reflections at the center of the main beams. This is a consequence of the fact that the gains of the antennas are best known in this direction. Such reflections occurred especially in December 1959. Their radar cross sections are on the average about 1000 square meters, the altitude of the satellite being 600 km and the distance from the receiver 700 km.

The radar cross section of the ion trail does not seem to depend very much on the altitude of the satellite. However, the present observational material is insufficient for a detailed study of this question.

Table 5 contains further the values of the radar cross sections calculated on the assumption that the reflection has taken place in the main beam. All these values are considerably greater than the radar cross section of the satellite itself. It is, therefore, evident that the satellite echoes cannot have come from the body of the satellite. Echoes from the satellite itself were never obtained, although several transits were traced in which a radar cross section of 2 to 10 square meters would have been sufficiently large to produce an echo. This can be taken to indicate that the radar cross section of Sputnik III was less than 10 square meters. The transit through the main beam lasted 5 to 10 seconds. Thus Faraday rotation, for instance, would not have been able to prevent observation of an echo.

4.3. Conditions for the occurrence of the ion trail

The diurnal distribution of the satellite echoes is shown in Fig. 21. Conditions for the occurrence of an ion trail seem to be most favourable immediately after sunrise and near sunset. In the night-time, conditions seem to be less suitable for the development of the trail. However, in this respect the present results are less reliable, because fewer observations were made at night than in the daytime (Table 2). The diurnal distribution of the satellite echoes may also have been influenced by auroral echoes. These made it impossible to perform observations, for instance, in the end of November and in the beginning of December, 1959. The transits of Sputnik III took then place in the afternoon. The echo distribution in Fig. 21 is similar in character to the diurnal distribution of diffuse auroral echoes in Alaska [Presnell et al.; 1959].

It can be seen from Table 4 that, during the time of the present investigation, there were periods of several weeks when no satellite echoes were observed. On the other hand, satellite echoes were often received on consecutive days. The occurrence of the echoes in groups seems to have some connection with the occurrence of auroras. In five instances (Dec. 14 and 15, Jan. 15, Feb. 15 and March 12) a satellite echo was observed on a day when there were also auroral echoes. Accordingly, since only 21 transits could be traced on days when there were auroral echoes (see 3.3), the occurrence of satellite echoes on such

Table 6.

Average occurrence of spread-F.

Month	At the time of satellite echoes (except M-echoes)	At the time of other long signals	At the time of auroral echoes
1959			
Aug. - Sept.	4.0	0.4	
October		2.8	
November	4.0	3.3	4.2
December	3.0	1.7	4.2
1960			
January	5.0	3.4	5.0
February	4.0	2.4	3.4
March-April	3.0	1.5	4.0

days was considerably above the average. In 219 transits on days without auroral echoes, there were only 9 satellite echoes (plus 6 M-marked echoes).

It is likely that auroras occurred in the region of the sky under observation, at times close to the transit of Sputnik III, also on other days when satellite echoes were observed. In order to confirm this idea, the occurrence of the spread-F phenomenon and the magnitude of the geomagnetic three-hour K-index were examined. The nearest station performing measurements of this kind is the observatory at Nurmijärvi (60° 30' N; 24° 39' E), about 40 km to the north from the transmitter. Nurmijärvi is, in fact, about 100 to 500 km to the south of the actual region of the ionosphere under investigation. Consequently, there may also have been local spread-F phenomena and disturbances of the geomagnetic field, which did not reach as far as 100 to 500 km to the north. However, it seems obvious that long-lasting disturbances cover a larger area than short-lived ones. For this reason the commonness of the spread-F was studied by examining its occurrence during five hours at the time of the transit. Table 6 shows the occurrence of the spread-F in the different months at the time of the satellite echoes (those marked with M excluded) and at the times when other long signals or auroral echoes were recorded. Number 5 denotes presence of spread-F during 5 hours; 4, during 4 hours, etc.

Table 7.

Average magnitude of the sum of two three-hour K-indices.

Month	At the time of satellite echoes (except M-echoes)	At the time of other long signals	At the time of auroral echoes
1959			
Aug. - Sept.	6.0	5.0	
October		4.2	
November	4.0	3.9	8.8
December	3.7	3.2	8.4
1960			
January	8.0	2.9	11.0
February	6.5	4.4	7.0
March-April	3.0	5.2	5.0

The table reveals a distinct correlation between the occurrence of spread-F and the satellite echoes. At the time of the satellite echoes (the M-echoes excluded) the occurrence of the spread-F has always been higher than at the time of other long signals. With two exceptions only, its occurrence during each satellite echo, according to the definition given above, has been at least 3.0. At the time of M-echoes it has been 2.0 on an average. Spread-F has been present, as a rule, also when there have been auroral echoes.

In a similar way, Table 7 shows the average sum of two three-hour K-indices at the time of long signals and auroral echoes, respectively. There is a correlation between the K-index sum and the occurrence of satellite echoes. However, it is not as evident as in the case of spread-F.

It seems evident that for the formation of a satellite ion trail, observable on 100 Mc, auroral ionization and spread-F in the vicinity of the satellite's trajectory are necessary. This also implies that a satellite-produced ion trail probably can be observed on 100 Mc close to the auroral zone only.

4.4. ESTIMATES ON THE SHAPE AND ION DENSITY OF THE ION TRAIL

The present study has already proved that the shape of the ion trail produced by the satellite must be such that reflection on 100 Mc occurs perpendicularly to the path only. The ion density and its distribution must be such that the radar cross section of the trail at the distance of 700 km on 100 Mc is of the order of magnitude of 1000 square meters, while the duration of the echo is 2.5 seconds on an average. The reflected signal must attain its maximum power approximately in the middle of this time interval. The Doppler shift of the echo must be small (less than 225 cps).

The condition that an echo can be obtained only at right angles to the trail implies that the ion trail has the shape of a long cylinder like that of a meteor.

On the basis of the results on the radar cross section, estimates can be made of the order of magnitude of the ion density in the trail. The reflection of radio waves from ion clouds of various shapes has been considered theoretically e.g., by Eshleman (1955). The reflection coefficient ϱ is determined by equation

$$\varrho = \frac{E_{sc}}{E_{inc}} \sqrt{\frac{2\pi^2 R}{\lambda}} \tag{4}$$

where E_{sc} is the field strength at the receiver of the wave reflected from the cloud, E_{inc} the field strength of the incident wave at the cloud, and R the distance between the receiver and the cloud.

According to Eshleman, the reflection coefficient of a cylindrical, underdense ion cloud is

$$\varrho_u = \frac{\mu_o e^2}{4m} q \frac{\int_0^\infty N(r) J_o\left(\frac{4\pi}{\lambda} r\right) r\, dr}{\int_0^\infty N(r)\, r\, dr} \tag{5}$$

where μ_o is the permeability of vacuum, e the electron charge, m the electron mass, q the number of electrons per unit length of the ion cylinder, and N(r) the electron density in the cylinder at a distance r from the axis.

Correspondingly, the reflection coefficient of an overdense ion cylinder is [Eshleman; 1955]

$$\varrho_o = \pi \sqrt{\frac{r_c}{2\lambda}} \tag{6}$$

where r_c is the radius at the critical ion density. Equations (5) and (6) have been derived on the assumption that the transmitter and the receiver are at same place, that the electrons in an underdense cloud reflect radio waves independently of each other, and that in an overdense cloud total reflection occurs on the surface, where the electron density exceeds the critical density. Furthermore, it has been assumed that the distance to the cloud is large in comparison with the cloud's dimensions and that, for overdense clouds, $2\pi r_c > \lambda$.

For the radar cross section of an ion trail the following equation can be derived:

$$\sigma = \frac{4}{\pi} F^2 \varrho^2 \qquad (7)$$

where F is the length of one half of the first Fresnel zone $\left(F = \sqrt{\frac{R\lambda}{2}}\right)$. Equation (7) is valid provided that the reflection takes place from a part of the ion trail having at least the length of the first Fresnel zone.

At a distance of 700 km and on a frequency of 98.82 Mc, F equals 1030 meters. The reflection coefficient must therefore be 0.027 in order that the radar cross section could be 1000 square meters. If the electron distribution is known, it is now possible to calculate from equations (5) and (6) the electron density in the ion trail. However, for the electron distribution only tentative assumptions can be made. In the cloud that may be produced ahead of the satellite [Krauss, Higgy, Crone; 1960], the electron density is probably highest on the axis. Behind the satellite a tubular cloud may be formed, in which there is low density on the axis and relatively high density in the shell. It can be assumed that the electron density in the ion trail of a satellite follows the Gaussian distribution law, as it does in the trails of meteors. The reflection coefficient 0.027 is then obtained, e.g., for an ion cylinder having a diameter of 1.5 meters, number of electrons per meter $3.6 \cdot 10^{13}$, and a maximum electron density $2.3 \cdot 10^{13}$ electrons per cubic meter. The figures are only approximate, as the maximum electron density is close to the critical value. The diameter of the cloud has been defined so that the density on its outer edge is 37 per cent of the maximum density [Eshleman; 1955]. If the ion trail is tubular, $4.6 \cdot 10^{13}$ electrons per meter are sufficient to produce the same reflection coefficient when the tube diameter is 2.5 meters, the thickness of the shell 0.5 meters, and the electron density in the shell $2.3 \cdot 10^{13}$ electrons per cubic meter. The different manner of distribution of electrons in an underdense ion trail does not alter the order of magnitude of the total number of electrons producing a given reflection coefficient. The number of electrons must therefore be about 10^{13} electrons per meter when the reflection coefficient on 100 Mc is 0.027 and the trail has a diameter of a few meters.

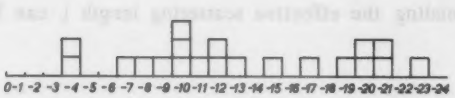


Fig. 21. Diurnal distribution of satellite echoes (each square corresponds to one echo).

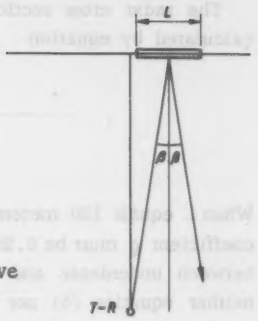


Fig. 22. Reflection by an effective scattering length L.

In order that the echo should have a duration of 2.5 seconds, when the reflection takes place from the length of the first Fresnel zone, the density of the ion trail must remain nearly unchanged during this time. This is unlikely, although possible, depending, amongst other things, on the shape of the satellite, and the velocity and direction of motion of the ion particles prior to formation of the trail.

However, the echo obtained from the ion trail of a satellite on 100 Mc may last 2.5 seconds though the trail itself disintegrates much quicker. This can be seen to be true if one assumes that reflection takes place from a part considerably shorter than the first Fresnel zone. This part can be called the effective scattering length L [Flood; 1957]. The effective scattering length travels with the satellite and its reflection properties are equivalent to a uniformly illuminated radiation aperture having the length L and the beam width (spacing between the zeros) $\theta = \frac{2\lambda}{L}$. If the aperture is illuminated at the angle β, its radiation beam will be deflected correspondingly away from the normal by the angle β (Fig. 22). For the reflected signal to be observable in the direction of the transmitter, the beam width of the aperture must then be 4β (not 2β as has been stated by Flood), and consequently

$$L = \frac{\lambda}{2\beta} \qquad (8)$$

The reflected signal is observed in the receiver during a period in which the effective scattering length travels the distance corresponding to the angle 2β. For the orbital velocity of the satellite, 7 km/sec., distance 700 km and 2.5 seconds duration of the reflected signal, the effective scattering length is 120 meters according to equation (8). The ion trail of the satellite must then remain reflective for 100 Mc radio waves during 17 milliseconds only.

The radar cross section corresponding the effective scattering length L can be calculated by equation

$$\sigma = \frac{4}{\pi} L^2 \varrho^2 \qquad (9)$$

When L equals 120 meters and σ 1000 square meters, it follows that the reflection coefficient ϱ must be 0.28. This indicates that the ion trail is an intermediate case between underdense and overdense clouds, and according to Eshleman (1955), neither equation (5) nor equation (6) will give the right value for the reflection coefficient. As shown before, the reflection coefficient of an underdense Gaussian cloud with a diameter of 1.5 meters and a maximum electron density of $2.3 \cdot 10^{13}$ electrons per cubic meter, is 0.027. For an overdense trail with a critical radius of 0.5 meters and an electron density of $1.2 \cdot 10^{14}$ electrons per cubic meter, the reflection coefficient is 0.9. Hence, it is seen that, at the least in the center of the trail, the electron density must be close to the value of $1.2 \cdot 10^{14}$ electrons per cubic meter in order to make the reflection coefficient equal to 0.28.

When reflection on the ion trail takes place from a part considerably shorter than the first Fresnel zone, the echo will attain its maximum amplitude in the middle of the time interval during which it is observed. This is, as a rule, in accordance with the observations.

The coarse estimate made above shows that an electron density 10^{13} to 10^{14} electrons per cubic meter, persisting about 15 milliseconds, is sufficient to account for the observed echoes from the ion trail of the satellite. According to the results of the present investigation, the satellite cannot normally produce such high electron densities. This can occur only when auroral ionization is present. Auroral ionization has been observed on 106 Mc at an altitude of 300 km [Schlobohm, Leadabrand, Dyce, Dolphin, Berg; 1959], and visible auroras have been recorded before sunset even at 1000 km [Störmer; 1948]. It is therefore to be considered probable that auroral ionization occurs at an altitude of 100 to 1000 km, normally distributed along the geomagnetic lines of force and able to reflect radio waves only at right angles to these lines. The ion density may be temporarily and locally very high. When the satellite traverses such regions, it may produce a change in the ion distribution so that an ion trail of the kind described above will be formed.

III. SUMMARY

An investigation has been carried out in which certain echoes observed with a 100 Mc CW radar have been shown to be produced by the ion trail of Sputnik III. The ion trail echoes have been observed when the satellite has travelled close to the latitude circle 65 ^{o}N, approximately in west-east direction and at an altitude of 200 to 600 km. They have usually been obtained only when auroral ionization has been present and when spread-F phenomenon has occurred in the ionospheric soundings close to the observation site. The echoes have had an average duration of 2.5 seconds; the corresponding radar cross section at a distance of 700 km has been of the order of magnitude of 1000 square meters. The observations show that the reflection from the satellite-produced ion trail on 100 Mc is specular. On the basis of the radar cross section found, and the duration of the echoes, some estimates of the ion density and shape of the ion trail have been made.

REFERENCES

Bullough K., Kaiser T.R.; 1955: Radio reflections from aurorae-II; J. of atmosph. terrestr. Phys.; vol. 6 1955 p. 198.

Dieminger W.; 1958: Ground scatter by ionospheric radar; Avionics Res. Copenhagen, 1958.

Eshleman R.; 1955: Theory of radio reflections from electron-ion clouds; Trans. Inst. Radio Engrs. PG - AP; January 1959 p. 32.

Flambard A.; Reyssat M.; 1958 Ondes electromagnetiques et satellites - Echos des trainees, ionisees de satellites en haute frequence; L'Onde electr., December 1958, p. 830.

Flood W.A.; 1957: Meteor echoes at ultra-high frequencies; J. geophys. Res., March 1957 p. 79.

Hendricks C.D., Swenson G.W., Schorn R.A.; 1958: Radio reflections from satellite-produced ion columns; Proc. Inst. Radio Engrs., October 1958, p. 1763.

Krauss J.D.; 1958: Detection of Sputnik I and II by CW reflection; Proc. Inst. Radio Engrs., March 1958, p. 611.

Krauss J.D., Dreese E.E.; 1958: The Sputnik I's last days in orbit; Proc. Inst. Radio Engrs., September 1958, p. 1580.

Krauss J.D., Higgy R.C., Albus J.S.; 1958: Observation of the U.S. satellites Explorers I and III by CW reflection; Proc. Inst. Radio Engrs., August 1958, p. 1534.

Krauss J.D., Higgy R.C., Crone W.R.; 1960: The satellite ionization phenomenon; Proc. Inst. Radio Engrs., April 1960, p. 672.

Krauss J. D., Ko C. H.; 1957: Celestial radio radiation [Ohio State University Res. Found., AF 19 (604) 1591, May 1957] Columbus 1957.

Manning L. A., Eshleman V. R.; 1959: Meteors in the ionosphere; Proc. Inst. Radio Engrs., February 1959, p. 186.

Presnell R.I., Leadabrand R.L., Peterson A.M., Dyce R.B., Schlobohm J.C., Berg M.R.; 1959: VHF and UHF radar observations of the aurora at College, Alaska; J. geophys. Res., September 1959, p. 1179.

Roberts C.R., Kirchner P.H., Bray D.W.; 1959: Radio reflections from satellite-produced ionization; Proc. Inst. Radio Engrs., June 1959, p. 1156.

Schlobohm J.C., Leadabrand R.L., Dyce R.B., Dolphin L.T., Berg M.R.; 1959: High-altitude 106.1-Mc radio echoes from auroral ionization detected at a geomagnetic latitude of 43°; J. geophys. Res., September 1959, p. 1191.

Störmer C.; 1948: Statistics of heights of various aurora forms from Southern Norway; Terr. Magn. atmos. Electr., 54. 1948.

Tiuri M.; 1960: Investigations on the periodicity of radio reflections from aurorae; [Valtion teknillinen tutkimuslaitos (The State institute for technical research). Tiedotus (Report). Sarja II - Metalli. 4]. Helsinki 1960.

Unwin R.W.; 1958: The geometry of auroral ionization; J. geophys. Res., September 1958, p. 501.

Verma J.; 1958: Low-noise 30 Mc amplifier; Rev. Sci. Instrum., May 1958, p. 371.

THE LAST VOLUMES OF
ACTA POLYTECHNICA PHYSICS INCLUDING NUCLEONICS SERIES

(The predecessor of Acta Polytechnica Scandinavica)

Volume 3

Nr 1 SVARTHOLM, N: *Two Problems in the Theory of the Slowing Down of Neutrons by Collissions with Atomic Nuclei.* Acta P 177 (1955), 15 pp, Sw. Kr. 5: 00 UDC 539.185.7

Nr 2 BOLINDER, F E: *The Relationship of Physical Applications of Fourier Transforms in Various Fields of Wave Theory and Circuitry.* ACTA P 189 (1956), 22 pp, Sw. Kr 6: 00 UDC 517.512.2:621.37

Nr 3 BRUNDELL, P-O, and ENANDER, B: *The Neutron-Proton System with a Central Exponential Potential. II.* ACTA P 190 (1956), 13 pp, Sw. Kr 2: 00 UDC 530.145:539.185

Nr 4 BÄCKSTRÖM, M: *Einfache Theorie der Gaszirkulation in Sorptionskälteapparaten nach v. Platen und Munters.* ACTA P 195 (1956), 71 pp, Sw. Kr 8: 00 UDC 621.575

Nr 5 GRANSTRÖM, S A: *Loading Characteristics of Air Blasts from Detonating Charges.* ACTA P 196 (1956), 93 pp, Sw. Kr 10: 00 UDC 624.042.3:533.6.011.72

Nr 6 STRANDELL, N: *A Photographic Method of Studying the Spread of Trochoidal Electron Beams.* ACTA P 204 (1956), 13 pp, Sw. Kr 2: 50 UDC 621.385.16.537.533.7.087.5

Nr 7 ZIMEN, K E: *Diffusion von Edelgasatomen die durch Kernreaktion in festen Stoffen gebildet werden (Edelgasdiffusion in Festkörpern 1)*
INTHOFF, W, und ZIMEN, K E: *Kinetik der Diffusion radioaktiver Edelgase aus festen Stoffen nach Bestrahlung (Edelgasdiffusion in Festkörpern 2)* ACTA P 206 (1956), 7+15 pp, Sw. Kr 6: 00 UDC 533.15:546.29-16:539.17

Nr 8 BÄCKSTRÖM, M: *Entropy-Enthalpy Diagram for Water Vapour and Liquid Extended to Higher Temperatures and Pressures.* ACTA P 207 (1956), 23 pp, Sw. Kr 5: 00 UDC 536.722:536.75:621.1.01(084.21)

Nr 9 MEYER, N I: *Switching Time in P-N Junction Diodes with Built-In Drift Field.* ACTA P 210 (1957), 32 pp, Sw. Kr 5: 00 UDC 537.311.33

Nr 10 OLSEN, H, ROMBERG, Wand WERGELAND, H: *Reaction of Sound Waves and its Application for Absolute Measurement of Intensity.* ACTA P 226 (1957), 13 pp, Sw. Kr 7: 00 UDC 534.61

Nr 11 ANDERSSON, B J: *Studies on the Circulation in Organic Systems with Applications to Indicator Methods.* ACTA P 229 (1957), 19 pp, Sw. Kr 3: 00 UDC 612.13:532.574.8

ACTA POLYTECHNICA SCANDINAVICA
PHYSICS INCLUDING NUCLEONICS

Ph 1 FANT, C G M: *Modern Instruments and Methods for Acoustic Studies of Speech.* (ACTA P. 246/1958), 83 pp, Sw. Kr 7: 00 UDC 534.154:612.789.

Ph 2 STUBB, T: *The Measurement of Conductivity in Semiconductors with the aid of Microwaves.* (Acta P 259/1959) 14 pp, Sw. Kr. 7.00 UDC 537.311.33

Ph 3 STUBB, T: *Untersuchung über die Lebensdauer der Minoritätsträger in Germanium.* (Acta P 269/1960) 17 pp. Sw.Kr. 7.00 UDC 537.311.33

Ph 4 ROOS, MATTS: *Approximate gamma ray flux calculations outside a reactor core.* (Acta P. 273/1960) 24 pp. Sw. Kr. 7.00 UDC 539.122:621.039.538

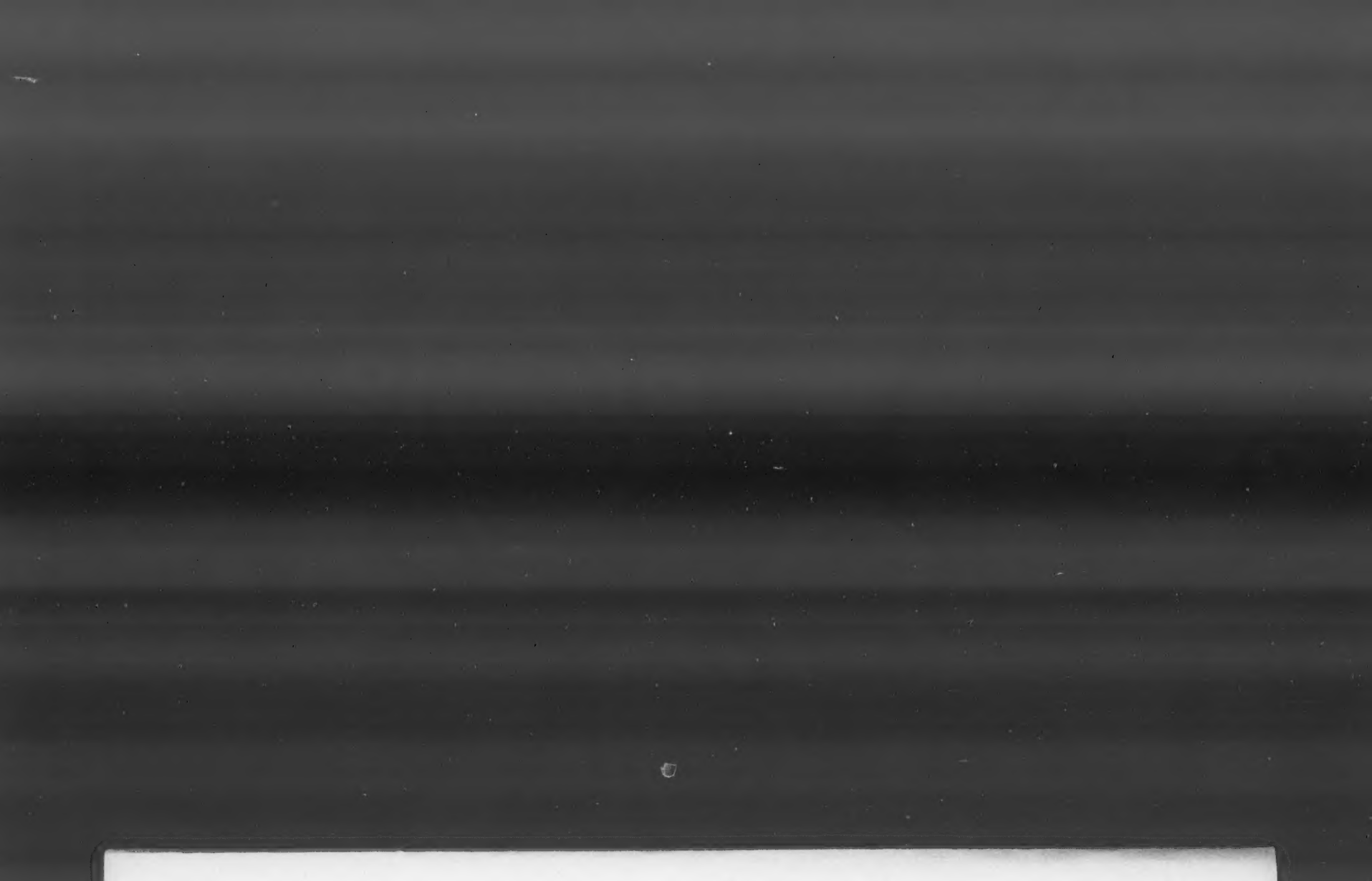
Ph 5 HÄRLIN, A: *Elementary Analysis and Heat Values* and WIDELL, T: *Enthalpy Diagram for Flue Gases.* (Acta P. 275/1960) 28 pp. Sw. Kr. 7: 00 UDC 536.662+536.722

Ph 6 CYVIN, SVEN J: *Mean Amplitudes of Vibration in Molecular Structure Studies.* (Acta P. 279/1960) 226+6 pp, Sw. Kr. 7: 00 UDC 539.19

Ph 7 JENSEN, ERLING: *General Theory on Spin Echoes for Any Combination of any Number of Pulses. Introduction of a simple «Spin-Echo Diagram».* (Acta P. 283/1960) 20 pp, Sw. Kr. 7: 00 UDC 539.143.4

Ph 8 MØRCH, K. A.: *Measurement of Total Acoustic Power of Sources of Sound in a Reverberation Chamber.* (Acta P 286/1960). 25 pp, Sw. Kr. 7:00. UDC 534.62

Ph 9 JÄÄSKELÄINEN, P.: *On Microwave Conductivity, Noise, and Oscillations of Gas Discharge Plasma.* (Acta P. 291/1960). 24 pp, Sw. Kr. 7:00. UDC 537.562:621.391.822.2

Ph 10 FORWALD, HAAKON: *Wave Phenomena in Compressed-Air Ducts.* (Acta P. 292/1961). 147 pp. Sw. Kr. 14:00. UDC 533.17:534.213.4-13:621.316.54

Price Sw. Kr. 7.00